Jet Propulsion Laboratory
California Institute of Technology

THE FUTURE OF AEROSPACE APPLICATIONS OF ADDITIVE MANUFACTURING: OPPORTUNITIES, OPTIMIZATION AND MODELING

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OUTLINE

Motivation

Modeling

Design Optimization

A Brief Review of Aerospace Applications

Conclusion

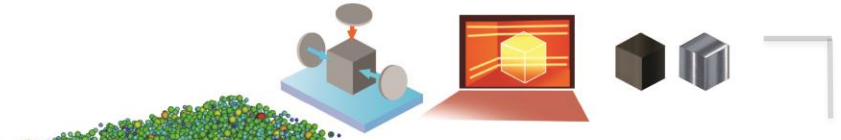
MOTIVATION

Why does anyone care?

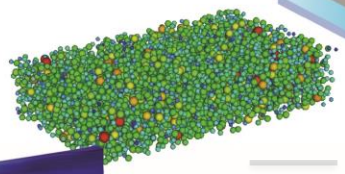
- Most additive models are developed independently
- Optimization will be the key to better designs in the future
- We need to find the right applications

MODELING

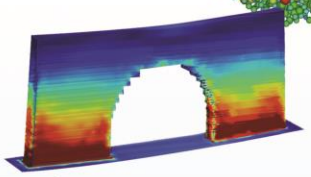
ADDITIVE MANUFACTURING MODELING



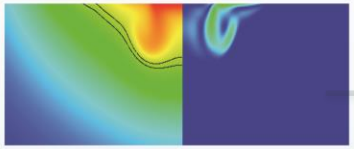
POST-PROCESS MODELING



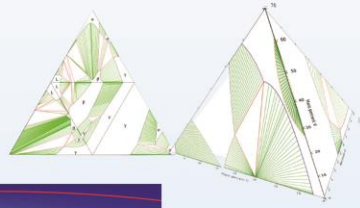
PROCESS MODELING



RESIDUAL STRESS MODELING



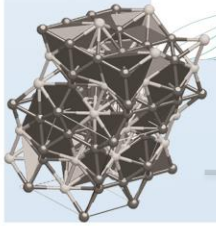
THERMAL MODELING



EQUILLIBRIUM / OFF-EQUILLIBRIUM MODELING

PHASE FIELD MODELING

KINETIC MODELING



ATOMISTIC MODELING

MODELING

Atomistic / molecular dynamic modeling

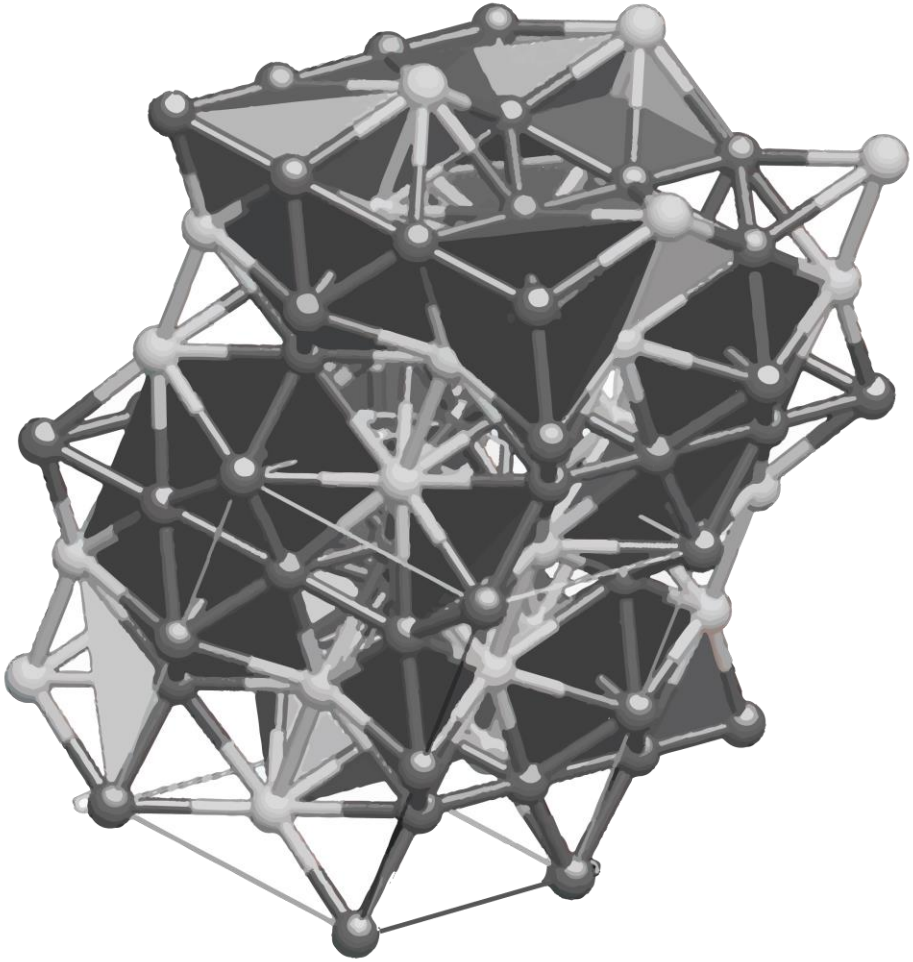


Image courtesy of NASA/ JPL

MODELING

Kinetic modeling

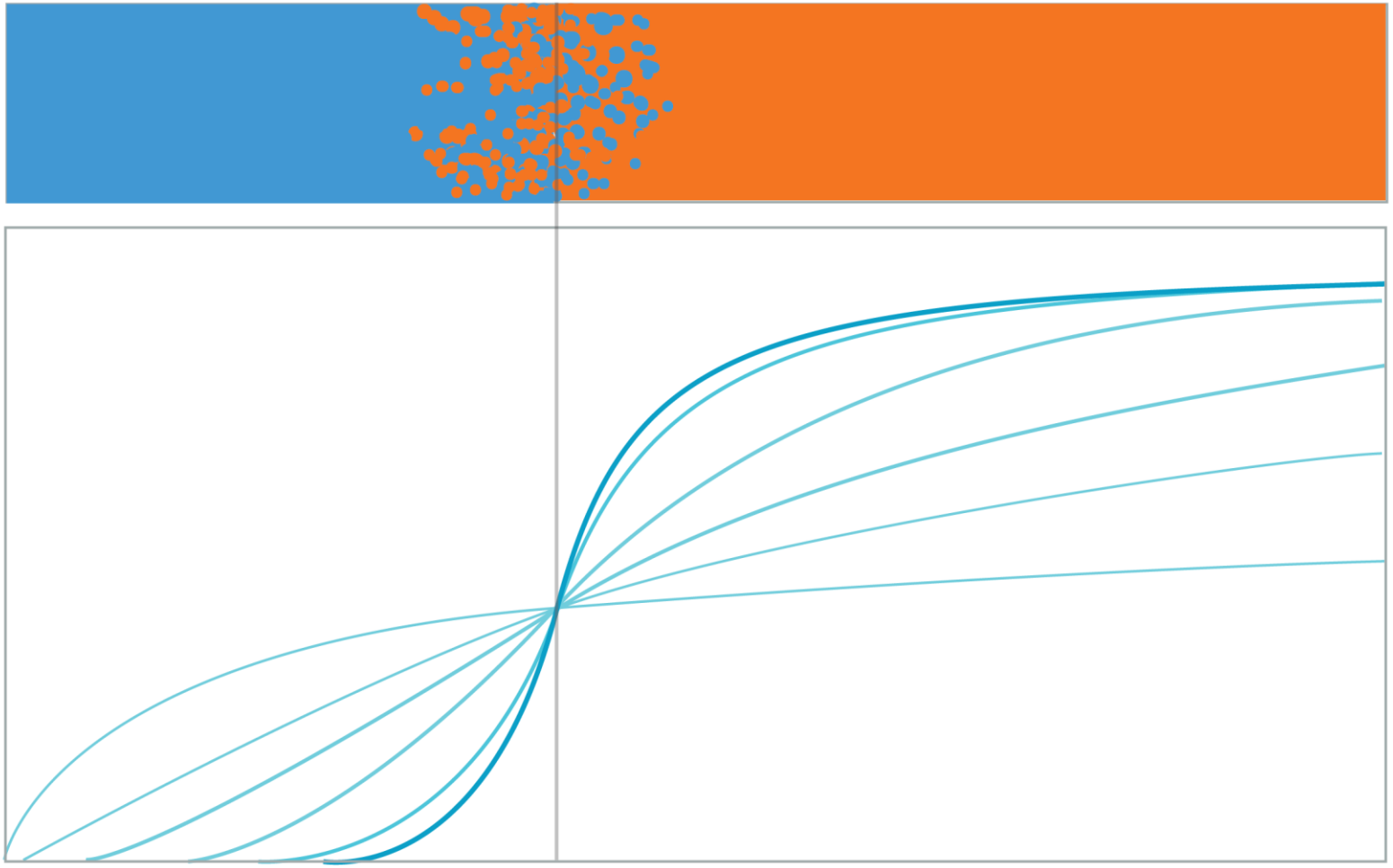
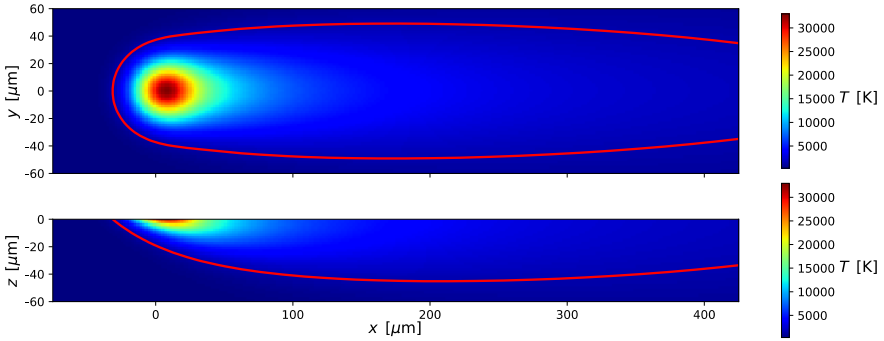


Image courtesy of NASA/ JPL

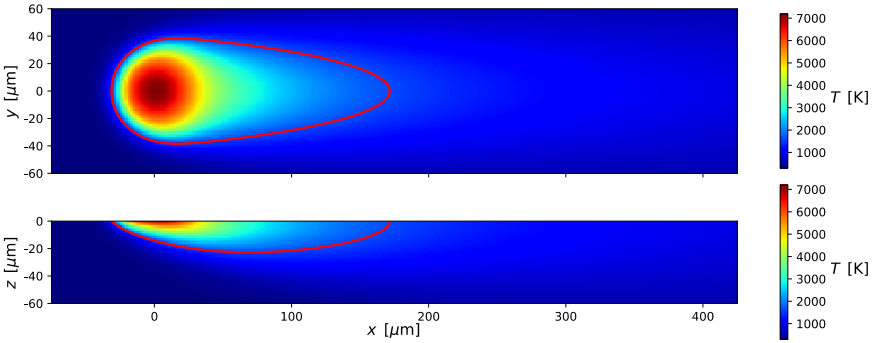
MODELING

Phase field modeling

No Evap. – Peak Temp around 33,000 K



Evap. – Peak Temp around 7000 K



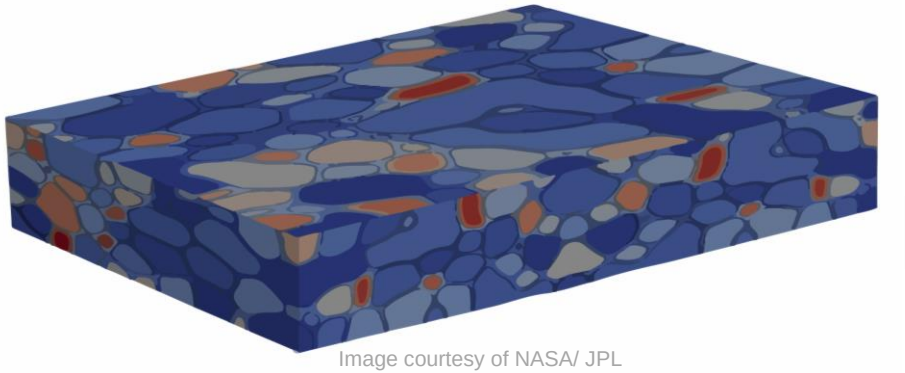
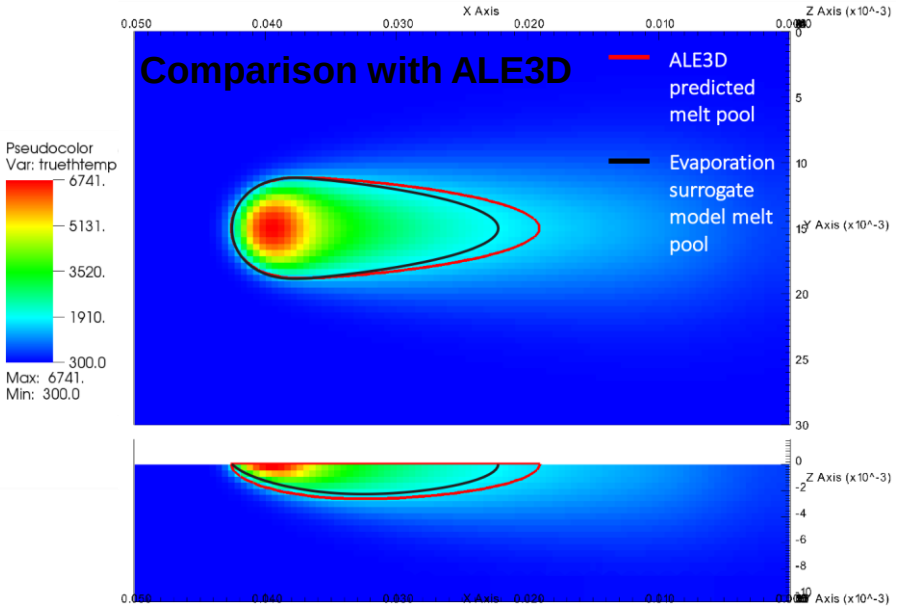


Image courtesy of NASA/ JPL



LLNL-PRES-744280

[Wolfer and Khairallah]
[UC Davis/ UC Irvine]

MODELING

Thermodynamic modeling

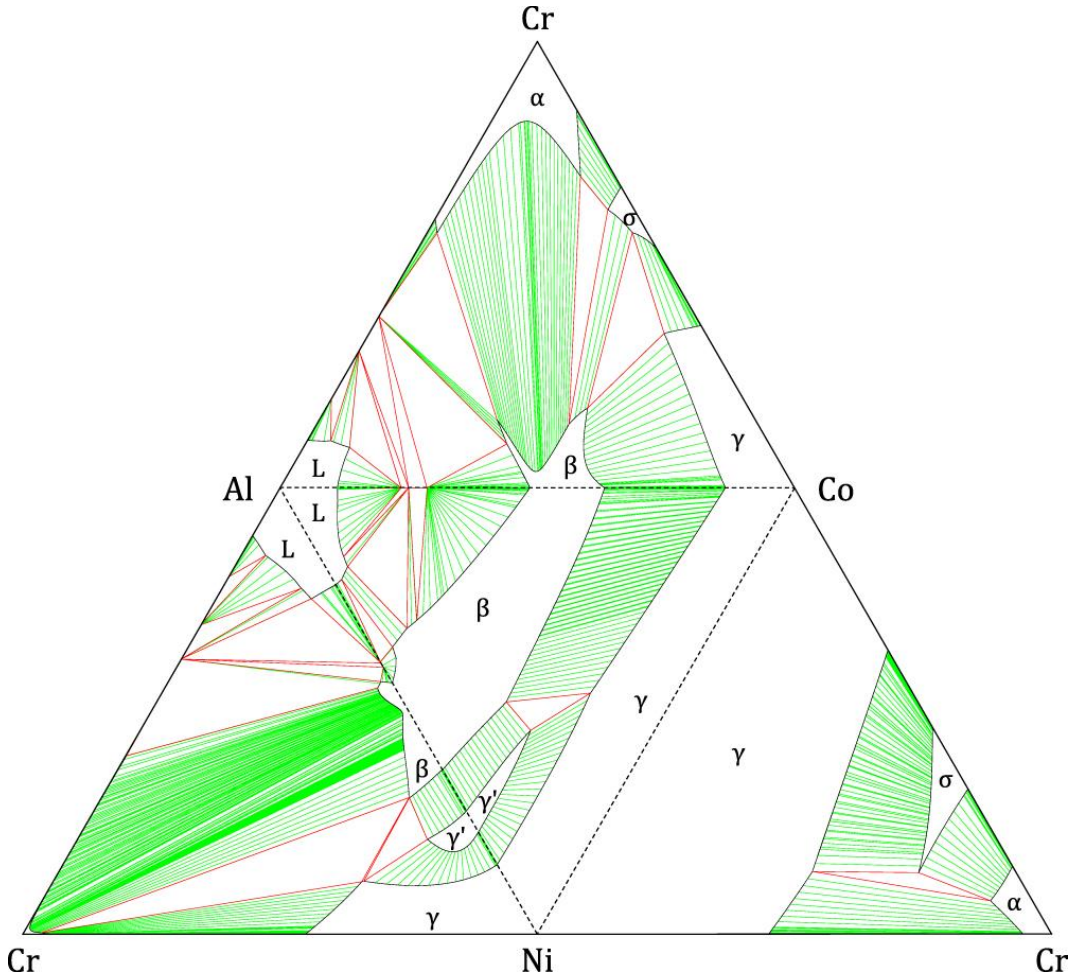


Image courtesy of NASA/ JPL

MODELING

Off-equilibrium thermodynamic modeling

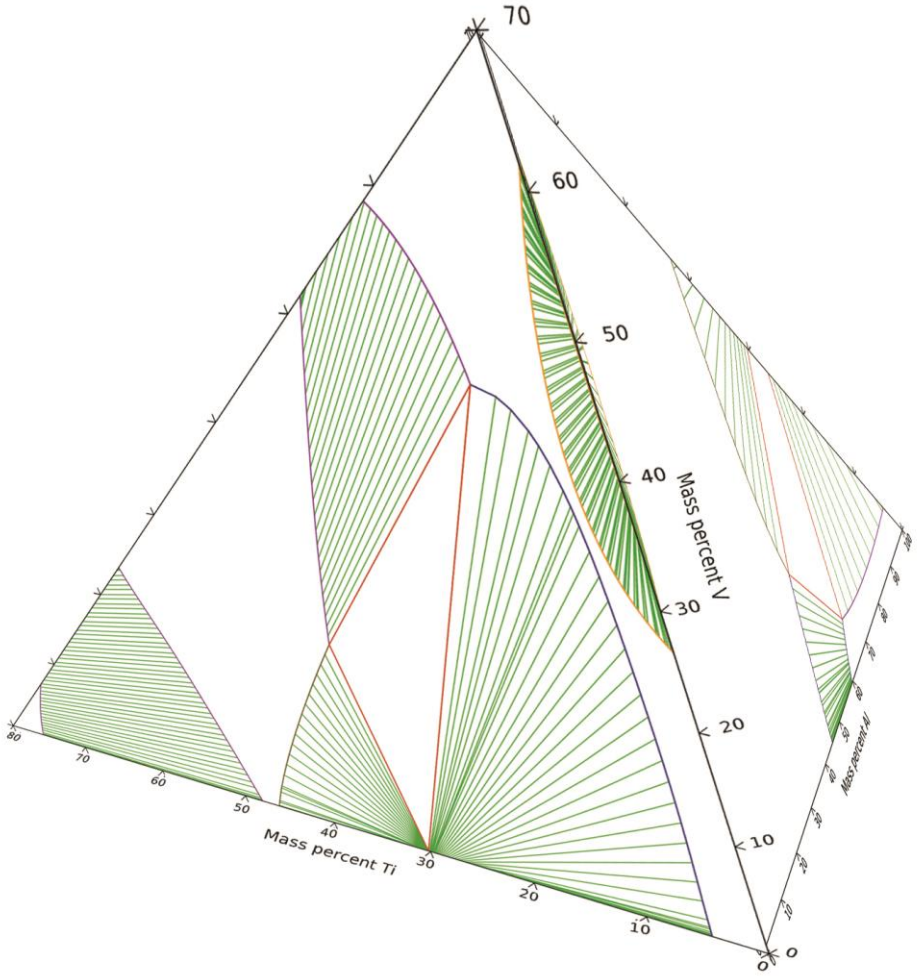
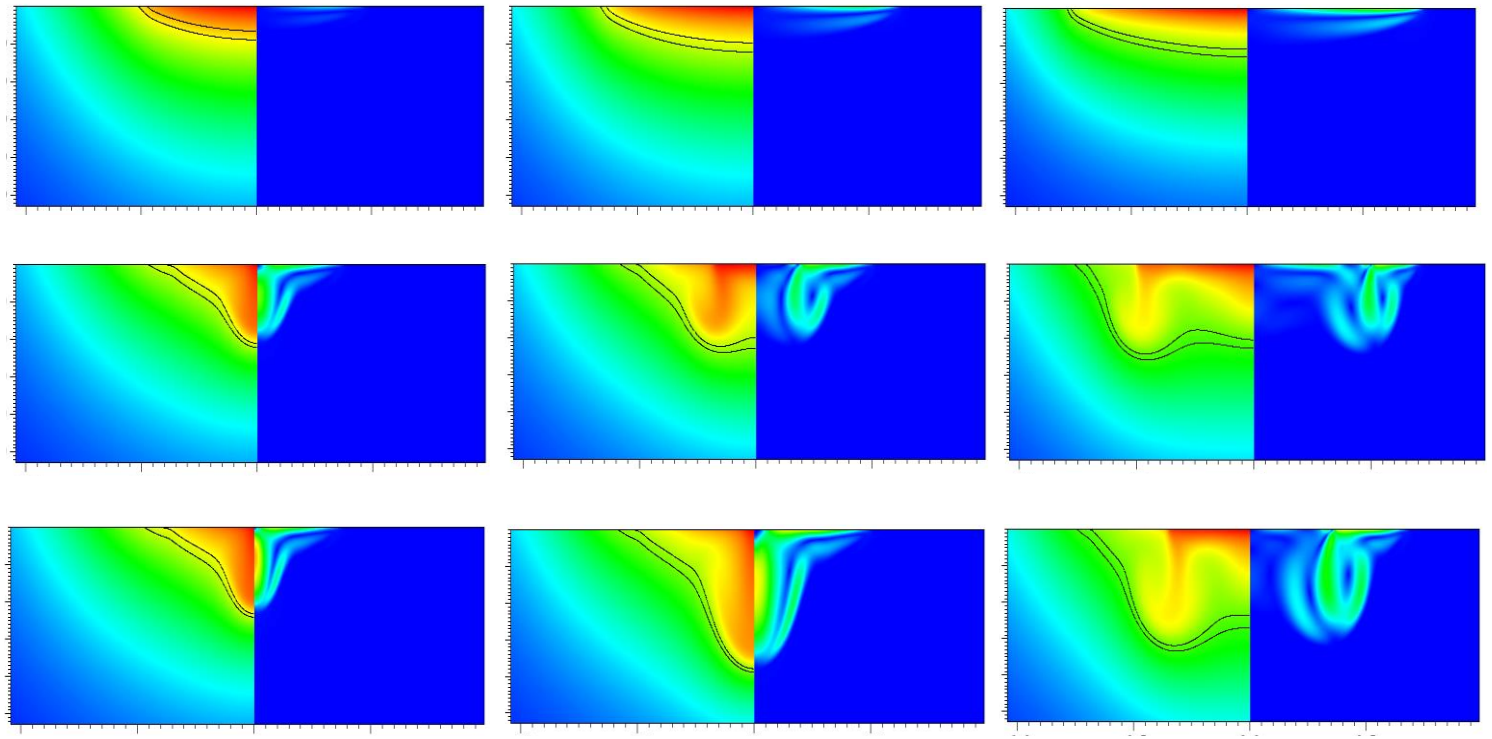


Image courtesy of NASA/ JPL

MODELING

Thermal modeling



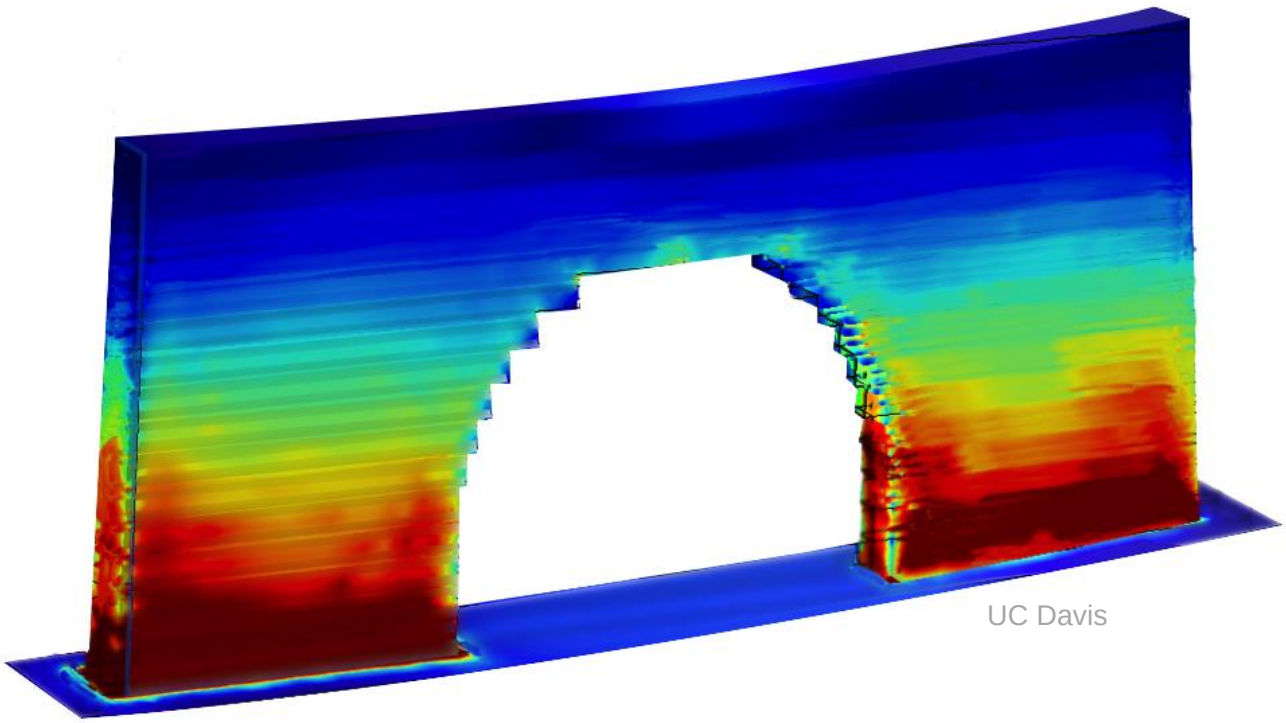
Lawrence Livermore National Laboratory

LLNL-PRES-744280

[Nourgaliev *et al.*, **APS/DFD 2017**, Denver, CO]

MODELING

Residual stress modeling



UC Davis

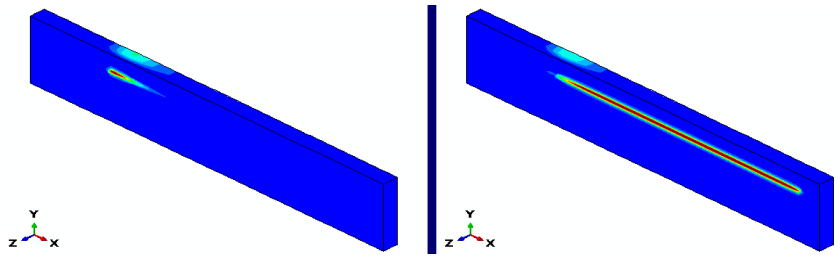
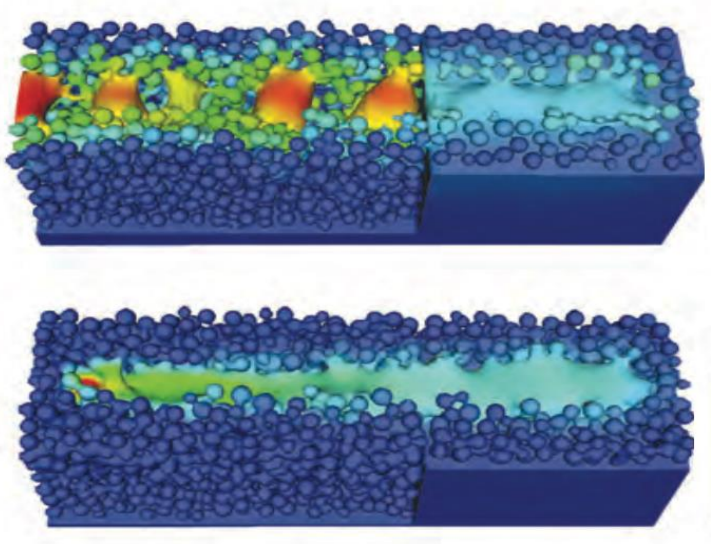


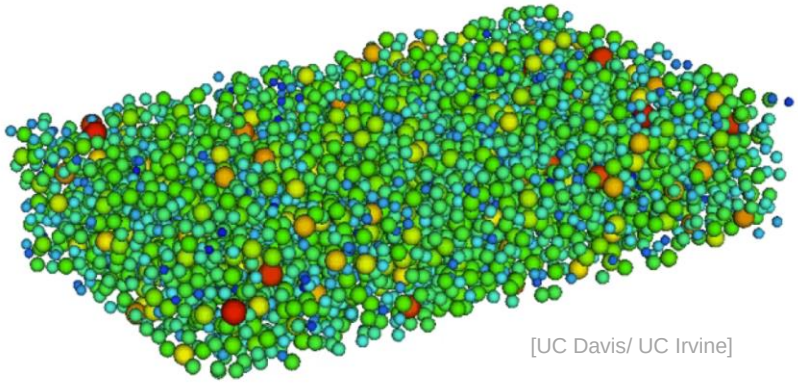
Image courtesy of NASA/ JPL

MODELING

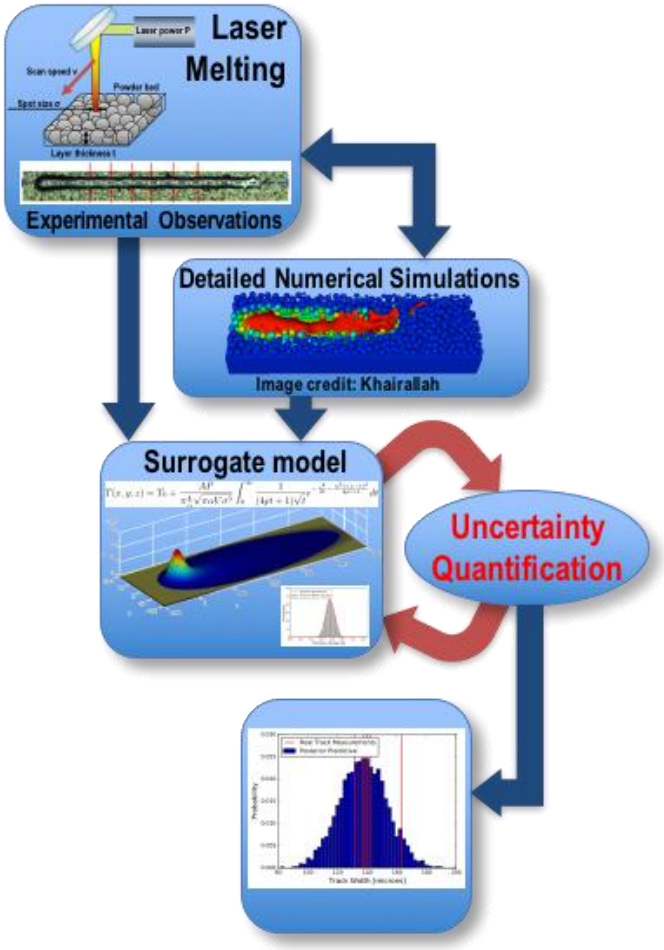
Process modeling



[From LLNL-PRES-744280, UC Davis/UC Irvine]



[UC Davis/ UC Irvine]

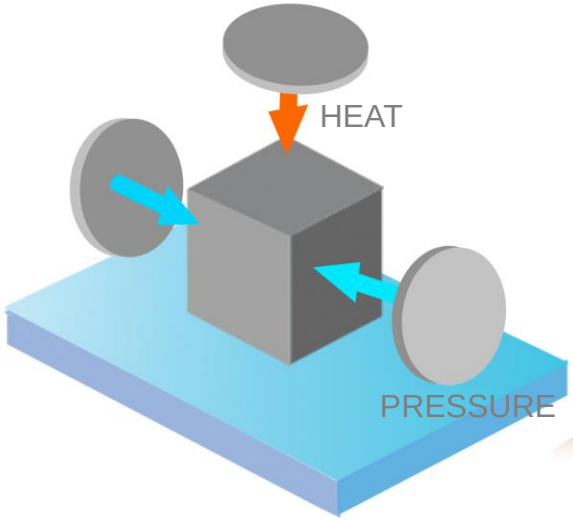


[UC Davis/UC Irvine]
Ref. LLNL-PRES-707401]

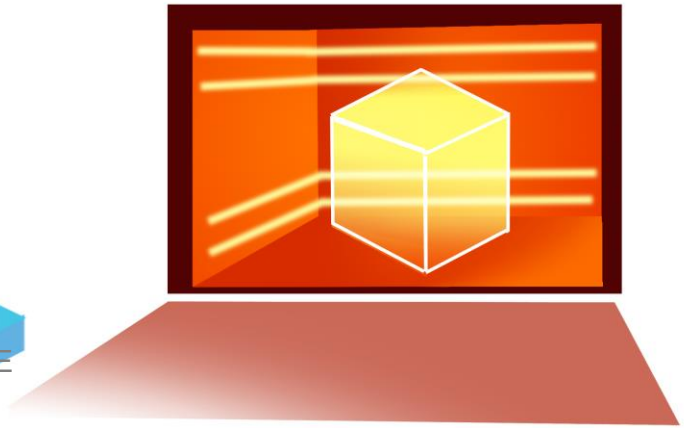
MODELING

Post-process modeling

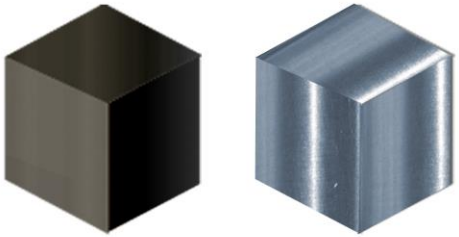
HIPING



HEAT TREATING

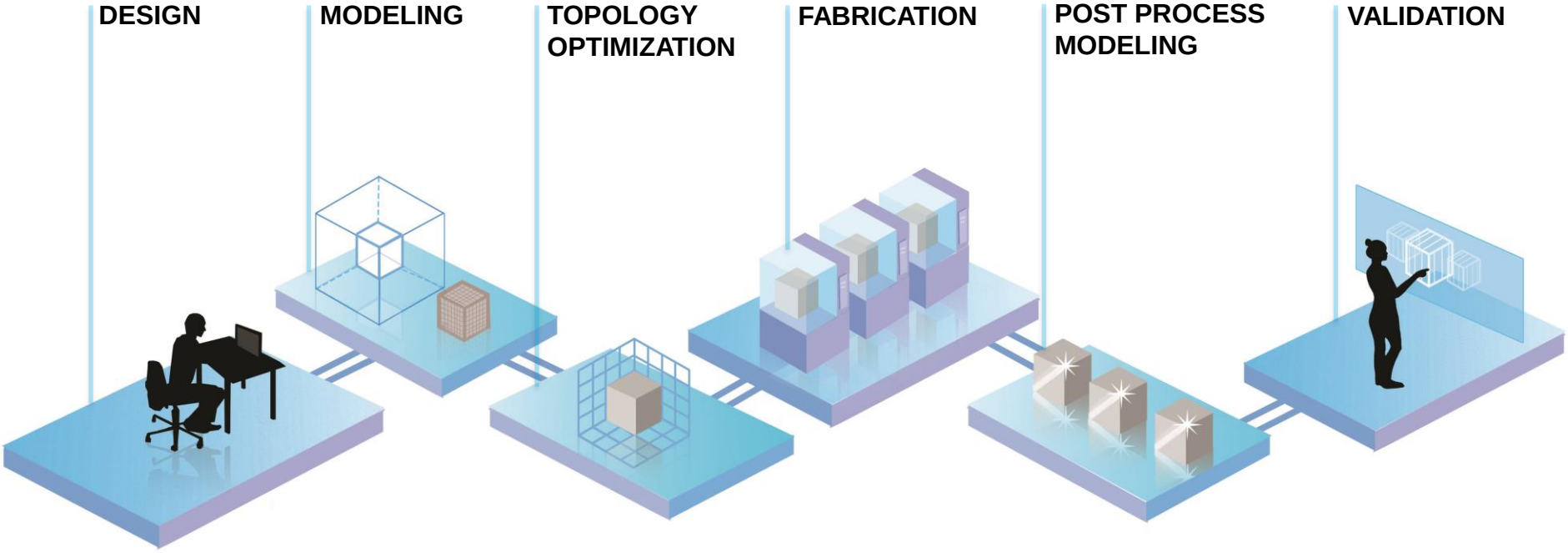


SURFACE FINISHING



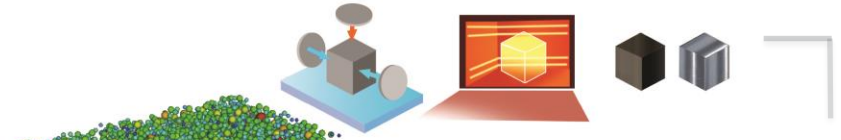
Images courtesy of NASA/ JPL

ADDITIVE MANUFACTURING

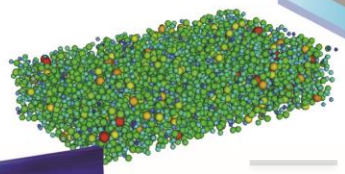


Images courtesy of NASA/ JPL

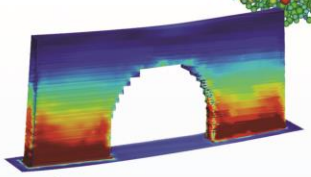
ADDITIVE MANUFACTURING MODELING



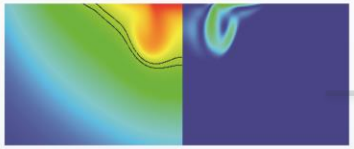
POST-PROCESS MODELING



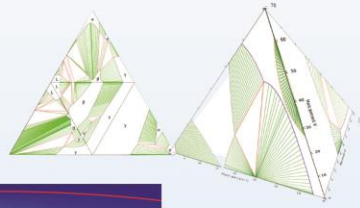
PROCESS MODELING



RESIDUAL STRESS MODELING



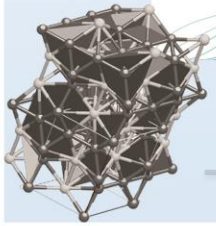
THERMAL MODELING



EQUILLIBRIUM / OFF-EQUILLIBRIUM MODELING

PHASE FIELD MODELING

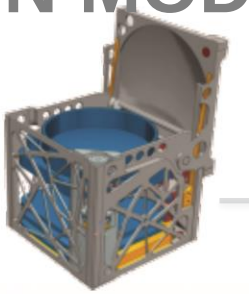
KINETIC MODELING



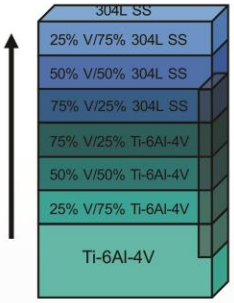
ATOMISTIC MODELING

DESIGN OPTIMIZATION

DESIGN OPTIMIZATION MODELING

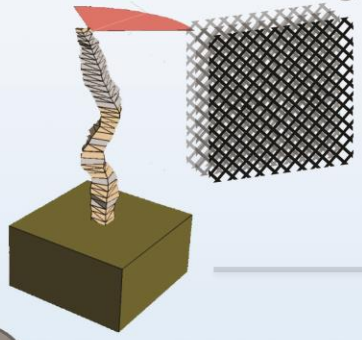


MULTIFUNCTIONAL DESIGNS



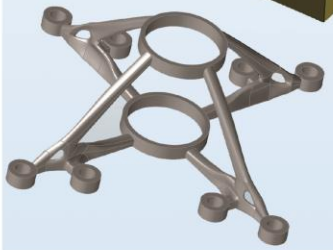
MULTIPLE MATERIALS

SUBTRACTIVE DESIGN



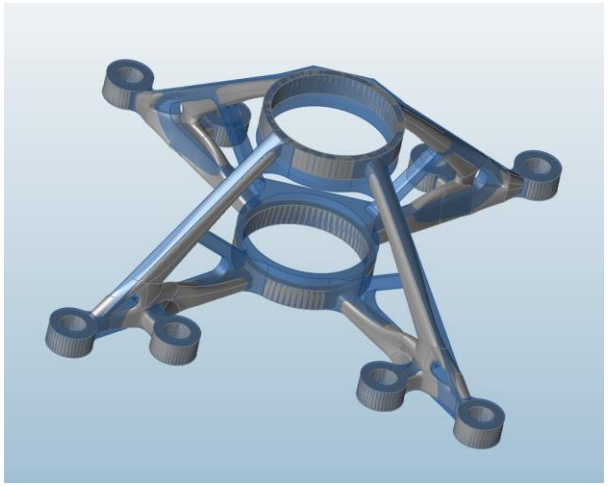
LIGHTWEIGHT DESIGN

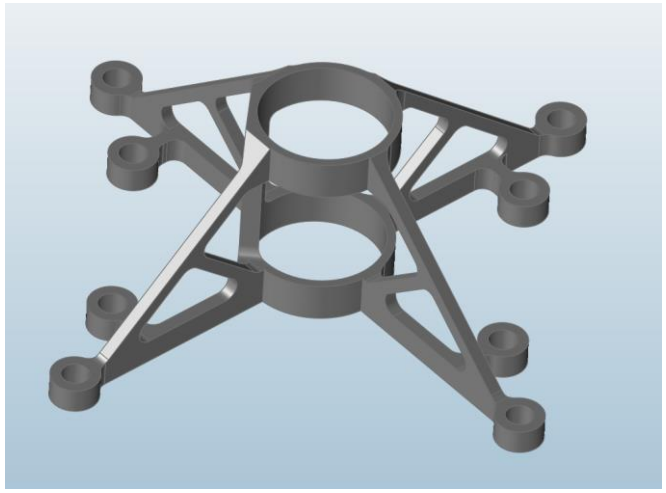
GENERATIVE DESIGN

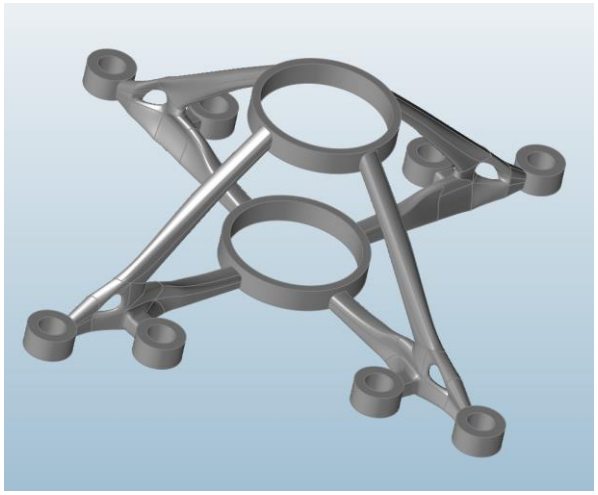


TOPOLOGY OPTIMIZATION

Topology Optimization

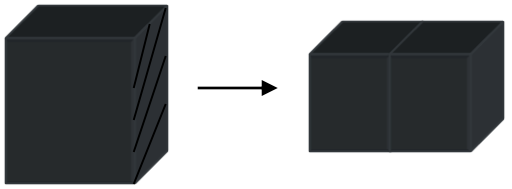


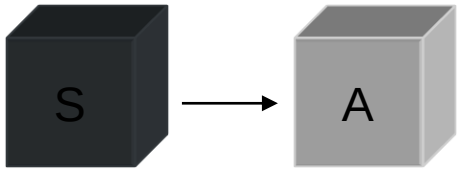




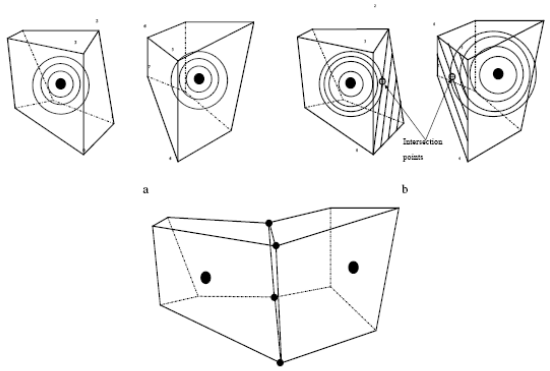
Images courtesy of NASA/ JPL

Generative Design

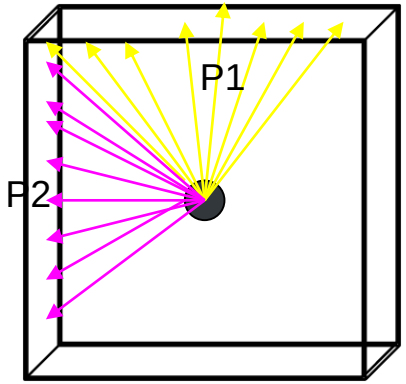


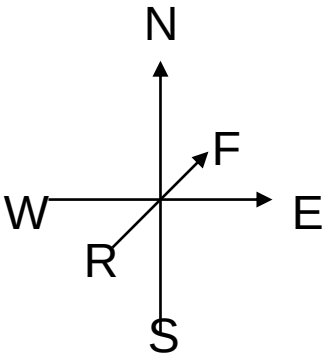


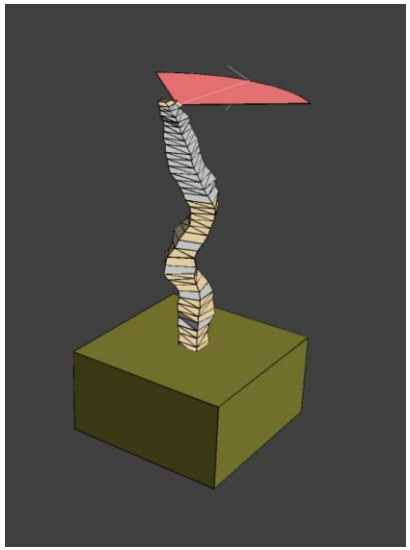
Cell adhesion

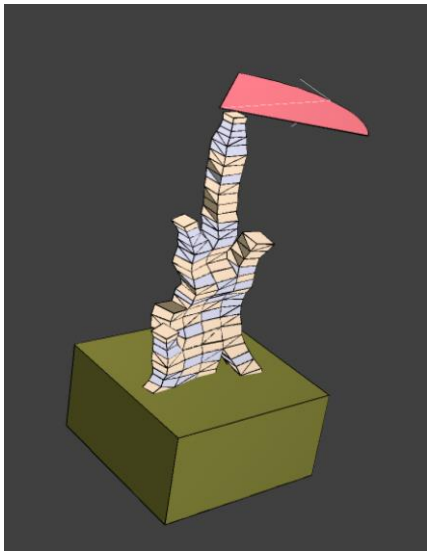


Protein Generation –
N number of proteins



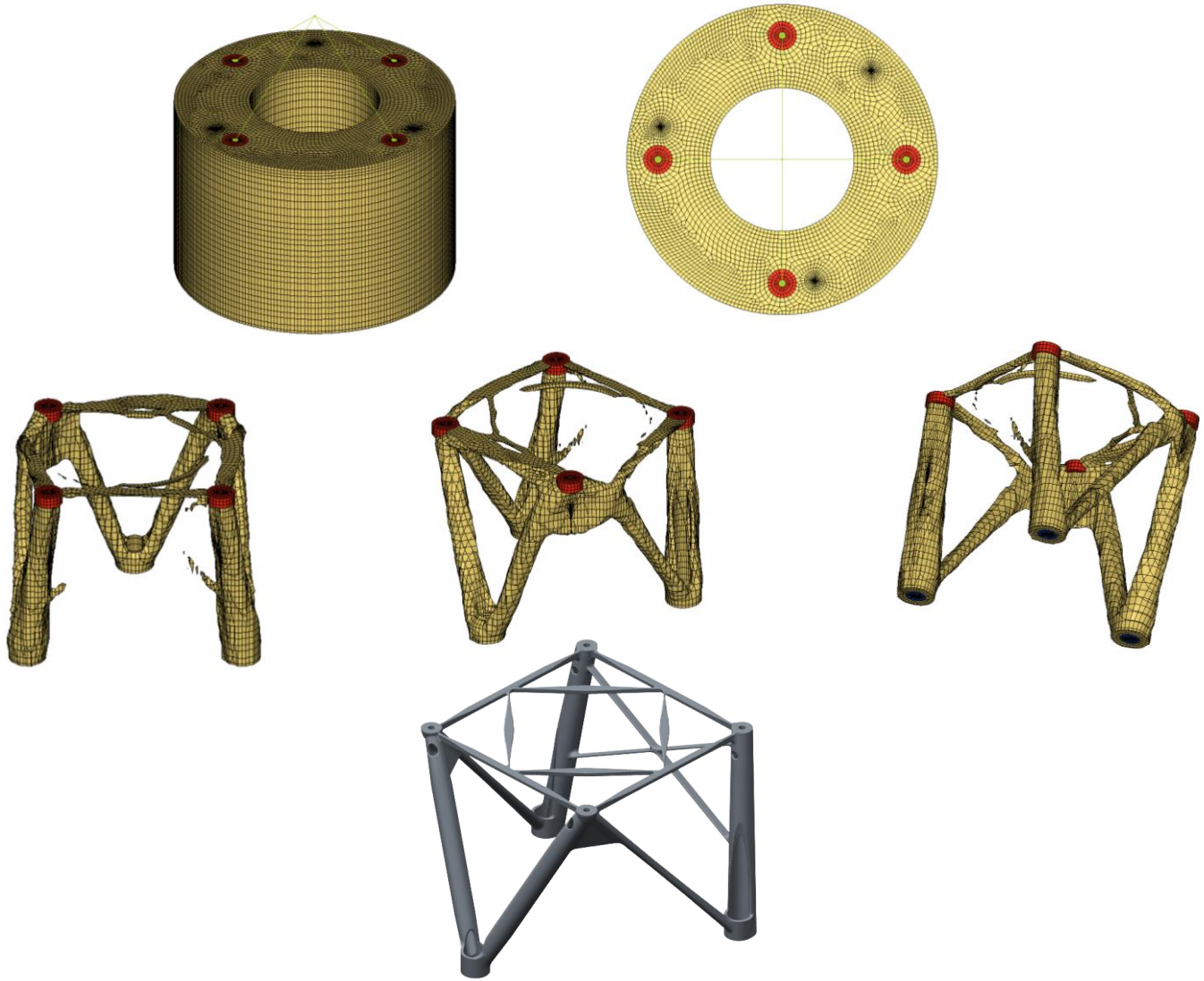






Images courtesy of NASA/ JPL/ Caltech

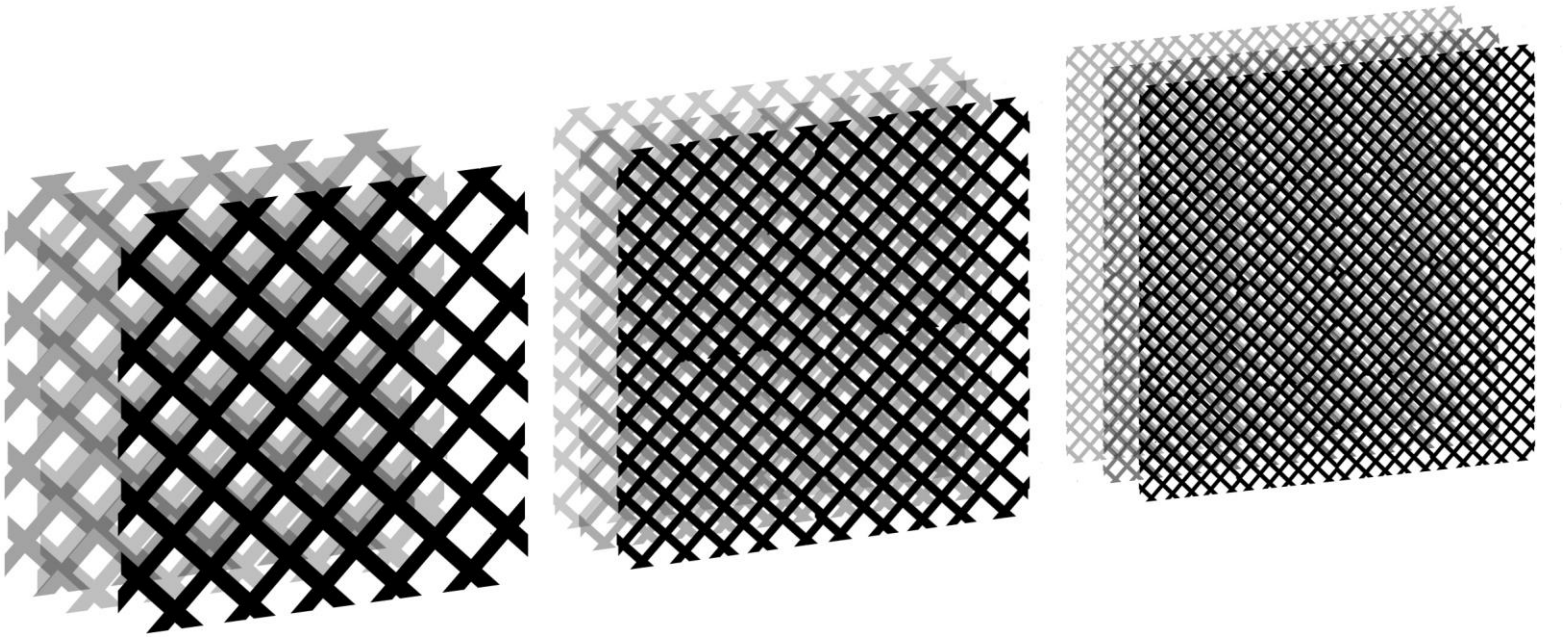
Subtractive Design



Images courtesy of NASA/ JPL

Lightweight Design

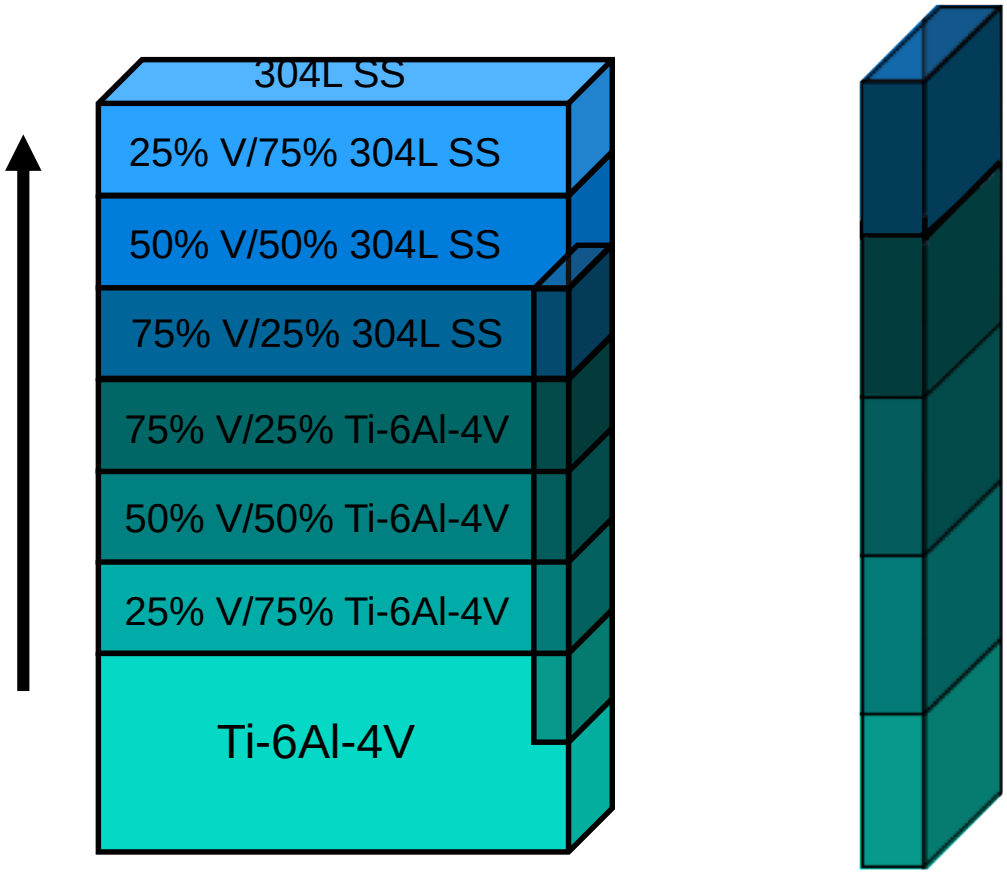
3-Dimensional Gridding, Scalable Gridding



Images courtesy of NASA/ JPL

Multiple Materials

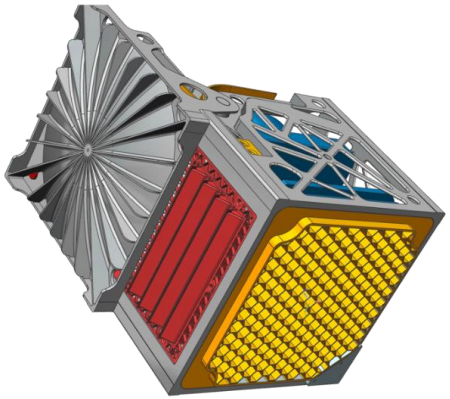
Additive Gradient

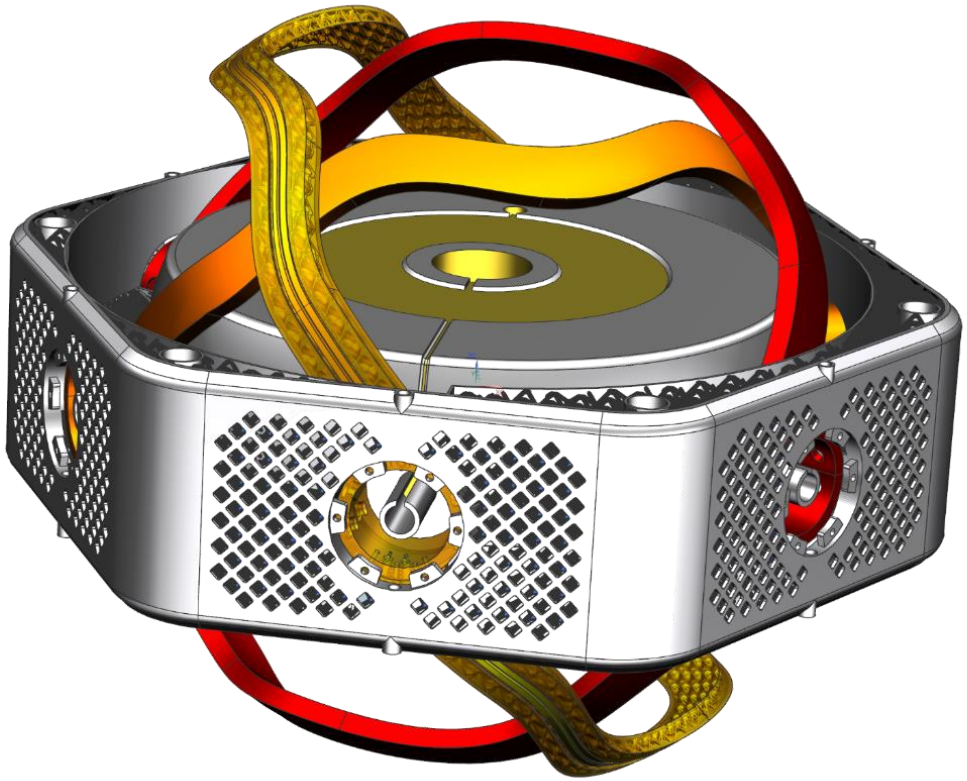


Images courtesy of NASA/ JPL

Multifunctional Designs

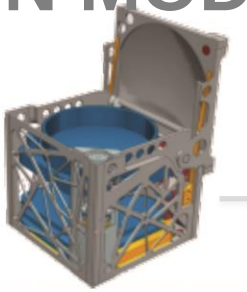
3-D and 4-D Multifunctional Systems



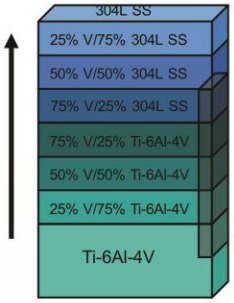


Patent pending NASA/JPL images by Raul Pollit-Casillas

DESIGN OPTIMIZATION MODELING

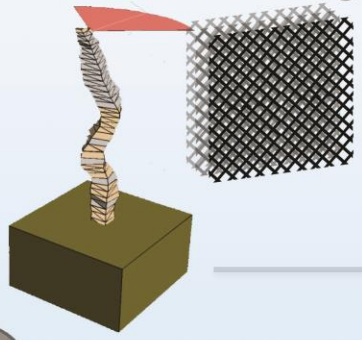


MULTIFUNCTIONAL DESIGNS



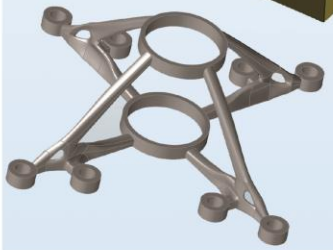
MULTIPLE MATERIALS

SUBTRACTIVE DESIGN



LIGHTWEIGHT DESIGN

GENERATIVE DESIGN



TOPOLOGY OPTIMIZATION

A BRIEF REVIEW OF AEROSPACE APPLICATIONS

Aerospace Areas Of Focus

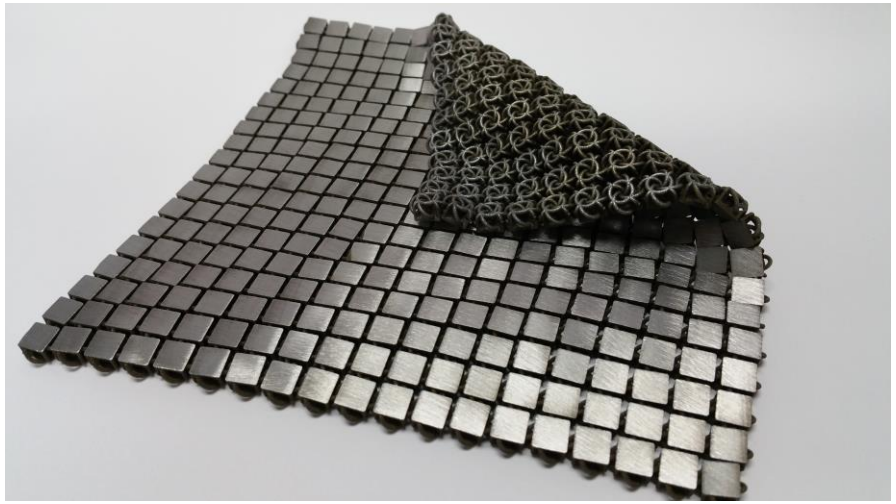
There are currently 7 areas of significant interest to aerospace that haven't received sufficient focus, yet offer significant benefits to their study

1. **New Design Frontiers**
   - **Gradients**
   - **Ceramics**
   - **Multi-materials**
   - **Multi-functional Structures**
2. **Combination of Multiple Assemblies**
3. **High Complexity Parts**
4. **In-Situ Fabrication**
5. **Mass Reduction**
6. **A Tool for Materials Research & Tailoring**
7. **In Situ Resource Utilization**

New Design Frontiers

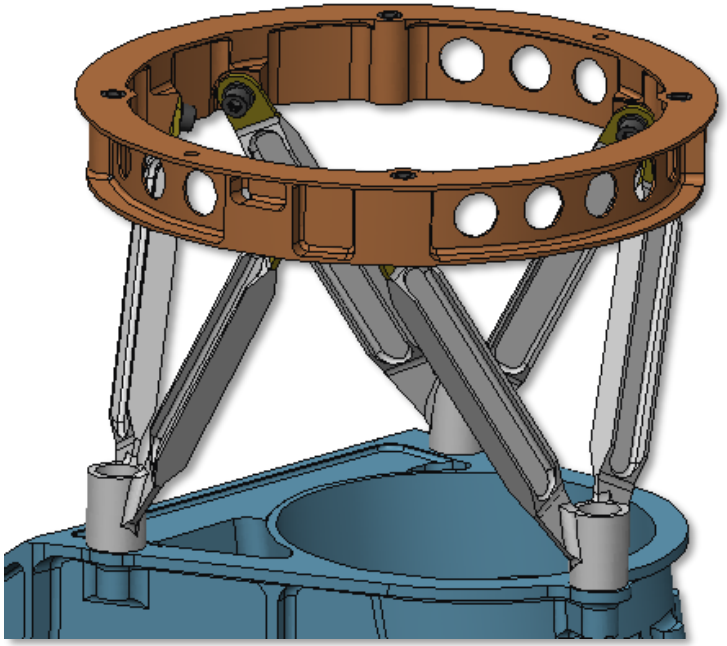
- **Gradients** – creating axial- or radially-graded materials enables enhanced design, such as tailored thermal expansion, thermal conductivity, or weldability, where required within the structure
- **Ceramics** – advanced properties, beyond purely structural (e.g. electrical, magnetic, dielectric) can be tailored as well
- **Multi-materials** – multiple materials systems (ceramics, metals, polymers) within the same structural geometry
- **Multi-functional Structures** – enabling smart structures with integrated functions such as embedded sensors within structural members
- **Fabrics** – allow for flexible applications with multiple properties and materials

Image courtesy Ashley Reichardt under the direction of Professor Peter Hosemann, UC Berkeley under a contract for JPL



JPL Image by Raul Polit-Casillas

Combination of Multiple Assemblies

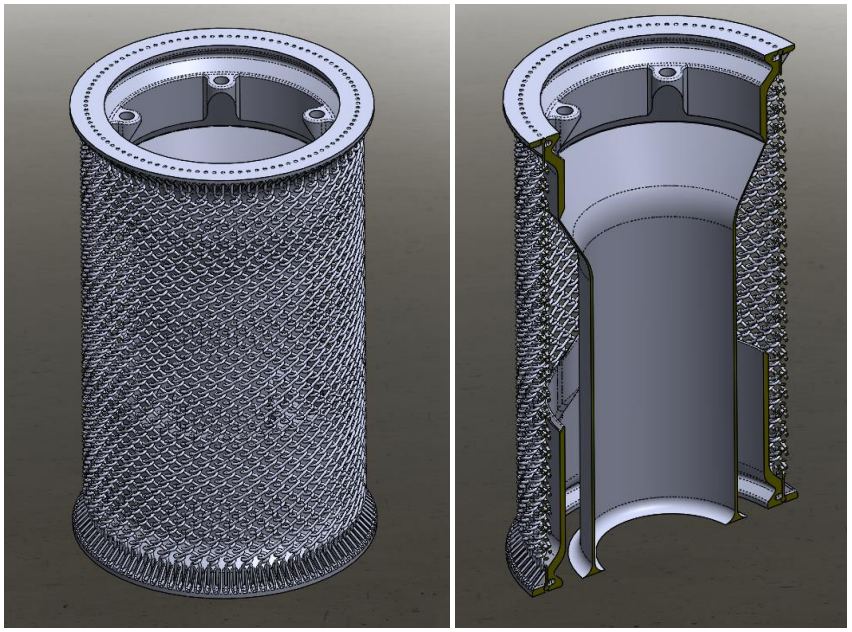


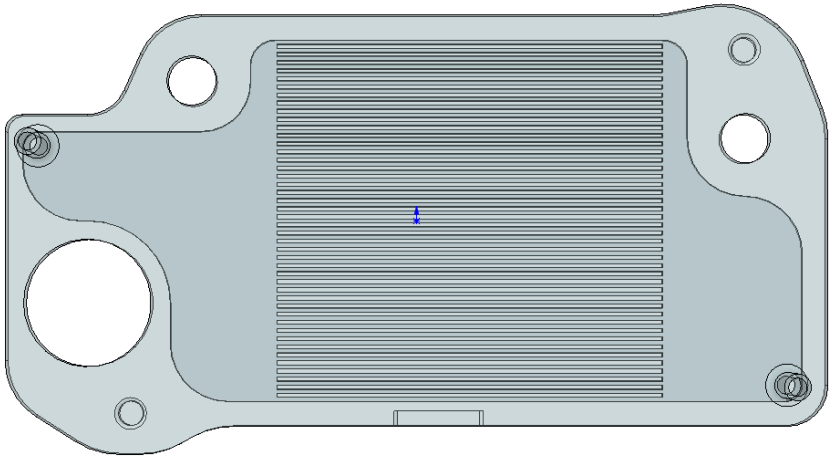
- The elimination of joints through the intelligent combination of multiple parts, coupled with design optimization methodologies
- Eliminate or minimize welding/brazing, bolted or riveted designs, which can simultaneously reduce weight, cost, complexity, integration and schedule
- Design optimization can result in unique or organic part architectures that cannot be accomplished for the same cost
  using conventional processing methods

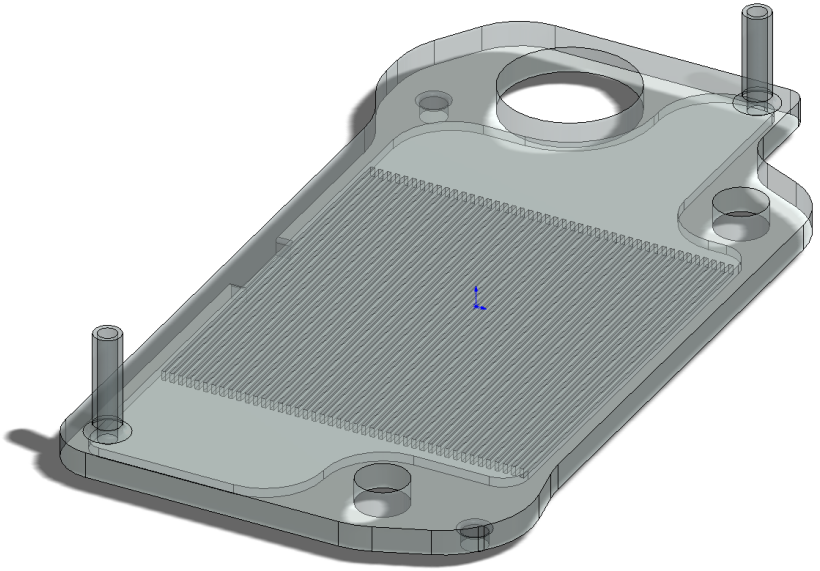
Images courtesy of NASA/ JPL

High Complexity Parts

- A major thrust, that has been underutilized in aerospace, is the creation of high complexity parts that have both internally and externally complex features
- Complex functions can now be tailored to meet space constraints, such as multiple attachment points with 3-D flow passages

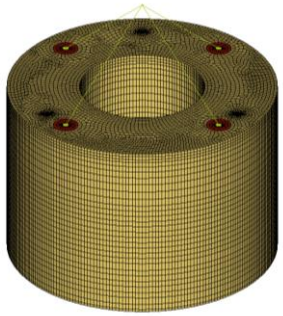


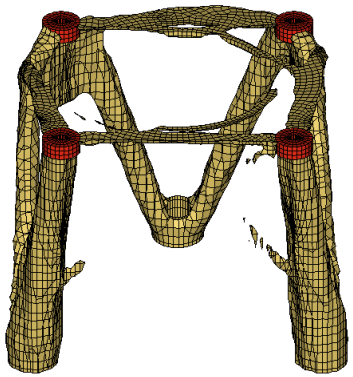




Images courtesy of NASA/ JPL

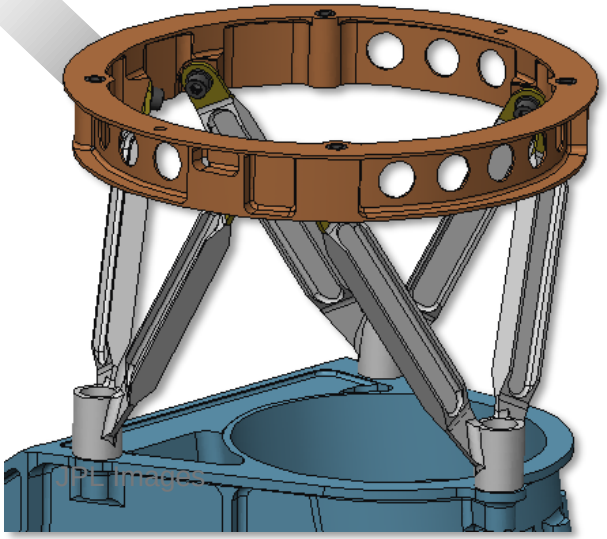
Mass Reduction





Mars Science Laboratory UHF Antenna Assembly

- Initial state (above left): 4-piece assembly with 6 bolted joints
- Final state (above right): 1-piece assembly
- 19% reduction in mass, as well as part count reduction

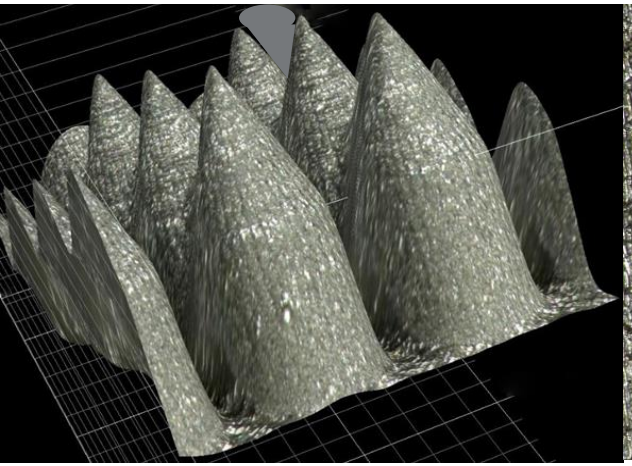


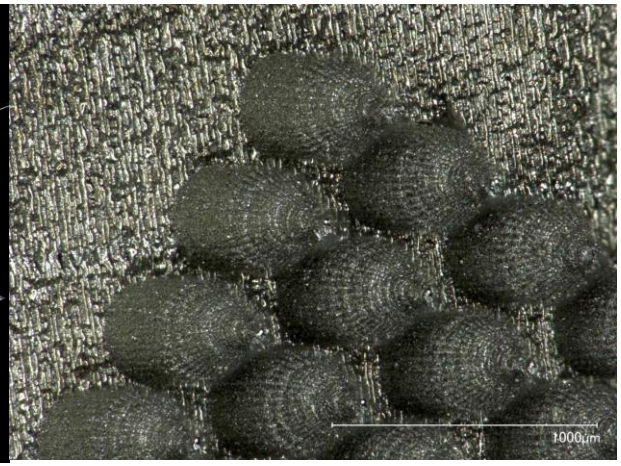
- Deep space exploration, and satellite launch, both have significant weight constraints ($10,000/lb to low earth orbit)
- Reduction of mass and part count can provide significant cost benefits or enable greater capability for a number of missions, particularly landers where the weight reduction goals are even more extreme

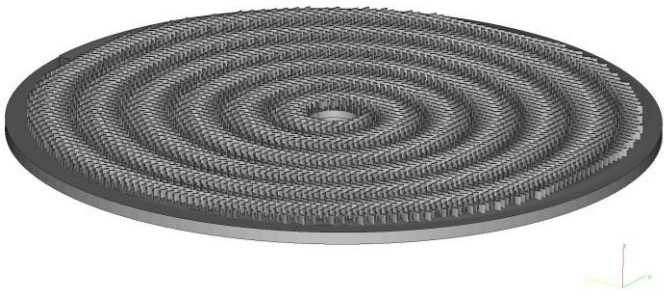
Images courtesy of NASA/ JPL

A Tool for Materials Research and Tailoring

- Development of new materials can be costly, particularly with more expensive alloy components or ceramic compositions.
  - Additive manufacturing allows for reduced material/lot sizes, which can enable research opportunities that otherwise may not be financially feasible
- Microstructural tailoring, which is impossible on a large scale for a number of processes, can be readily undertaken
  - In a single specimen, you can tailor a fatigue sensitive portion of a specimen with a fine-grained microstructure, whereas a coarse (e.g. faster build, slower dwell) microstructure will suffice for the remainder of the specimen, allowing micro-scale manipulation of the microstructure
  - The additive of selective agents, such as microspheres or toughening/hardening agents, akin to the original oxide dispersion strengthened superalloys, can be readily achieved and demonstrated for viability, further enabled by the rapid number of variations that can be procured in a single build

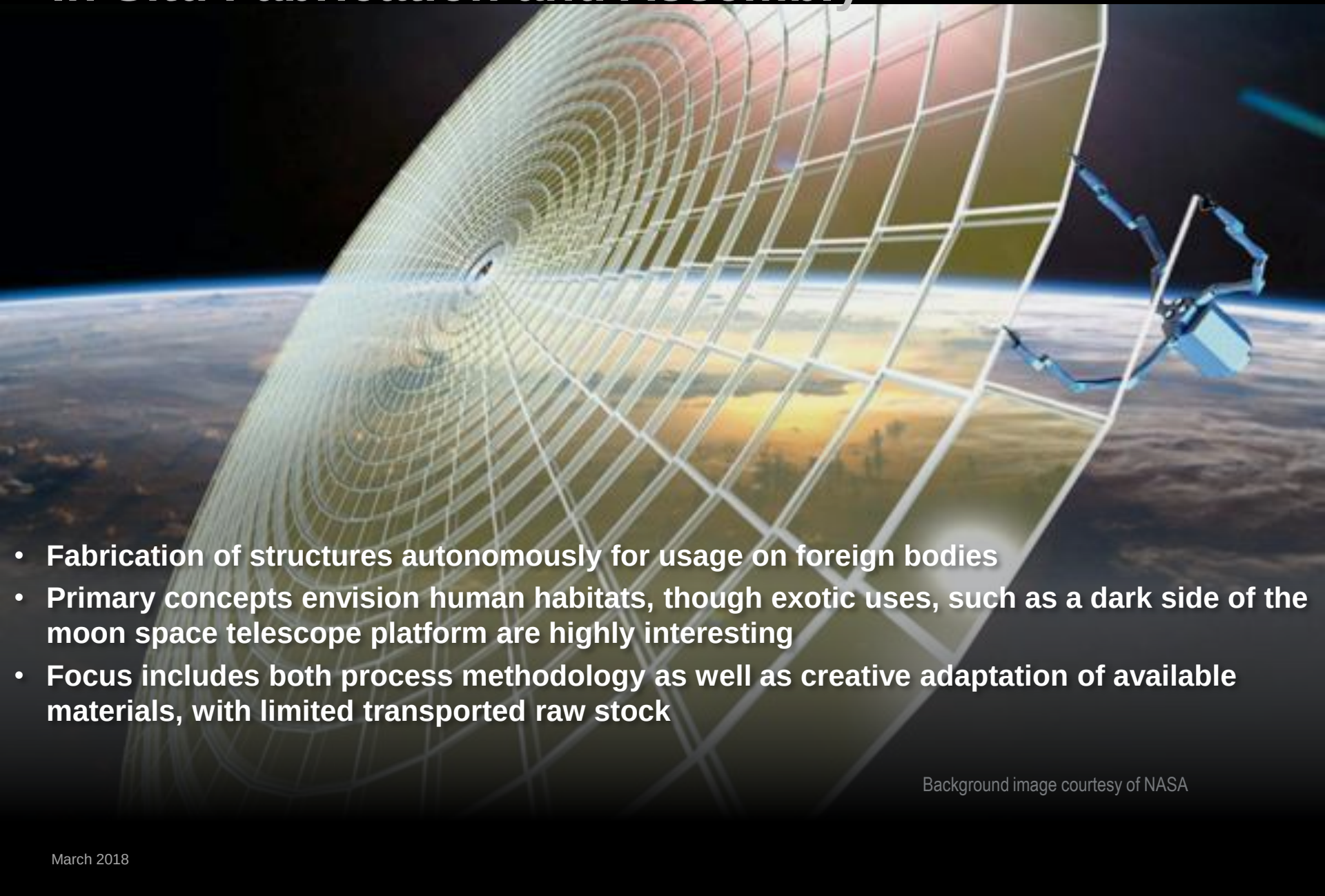






Images courtesy of NASA/ JPL

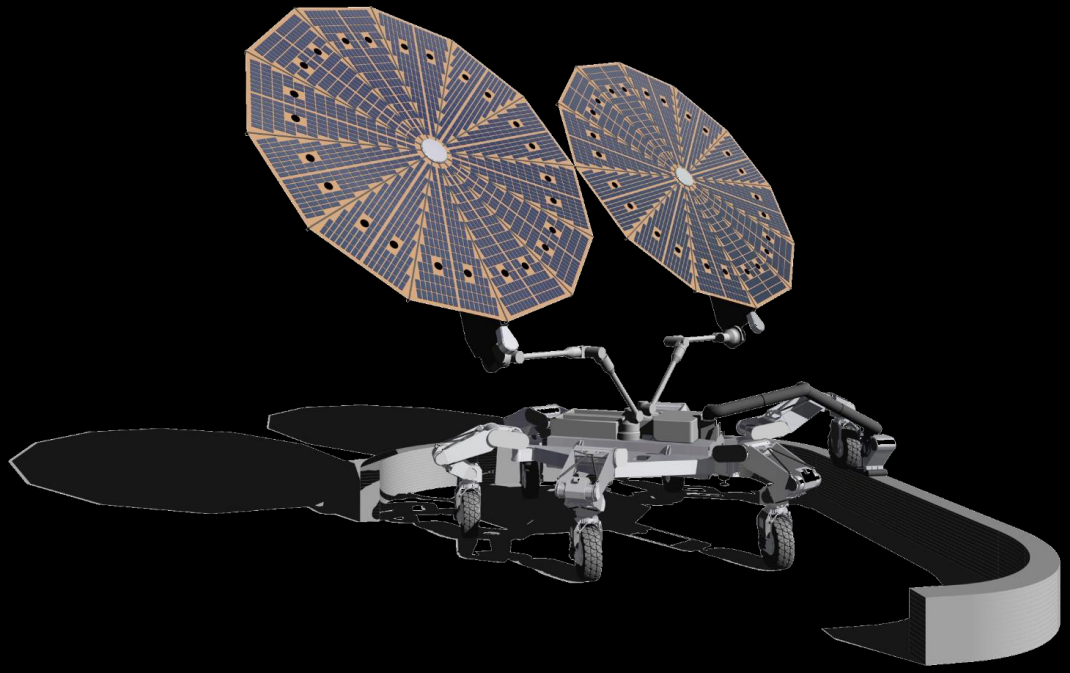
In Situ Fabrication and Assembly



- Fabrication of structures autonomously for usage on foreign bodies
- Primary concepts envision human habitats, though exotic uses, such as a dark side of the moon space telescope platform are highly interesting
- Focus includes both process methodology as well as creative adaptation of available materials, with limited transported raw stock

Background image courtesy of NASA

In Situ Resource Utilization



From: JPL/KSC Wilcox, Howe and Mueller

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Conclusion

Acknowledgements

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